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Energy reduction of building air-conditioner with phase change material in Thailand

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ABSTRACT

In this study, a concept of using phase change material (PCM) for improving cooling efficiency of an air-conditioner had been presented under Thai climate. Paraffin waxes melting point at around 20 °C was selected to evaluate the thermal performance by reducing the air temperature entering the evaporating coil. The model of PCM celluloid balls had been performed with the air-conditioner. Moreover, the mathematical model of the air-conditioner with the PCM storage was developed and verified with the testing results. From the study results, it could be seen that the simulated data agreed quite well with the experimental result at the discrepant around 2–4%. Finally, the model was used to analyze the economic result which was found that the electrical consumption of the modified air-conditioner could be decreased 3.09 kW h/d. The electrical power consumption of the modified unit was 36.27 kW h/d at the operating time 15 h/d compared with 39.36 kW h/d of the normal unit at the operating time 12 h/d. The saving cost of the PCM bed could be 9.10% or 170.03 USD and the payback period was 4.15 y.

1. Introduction

Phase change material (PCM) for using in office building is studied in various literature by applying for heating and cooling processes. In the heating process, PCM is used to warm the air before entering the room which reduces the electrical power of the air heater as presented by Kedl and Stovall [1], Salyer and Sircar [2] and Neeper [3,4]. For the cooling process, the main electrical energy consumption is devoted to air-conditioning system. Therefore, it is necessary to find techniques those could be used to reduce the load of the machine or to enhance its performance. Some researchers have used phase change material (PCM) as a tool to reduce cooling load by utilizing the cool ambient air in the nighttime which is used to charge the latent heat capacity of the PCM by freezing the material and the stored energy is released back to the occupied space to handle the heat gains during daytime.

Using of PCM in the energy building has been presented in many literatures. Uros et al. [5] presented an alternative method of cooling and ventilating buildings by integrating PCM into ceiling board of a building. Outside cool night air could be introduced into the space and it was used to cool the building interior and the PCM storage. During the daytime, hot indoor air was circulated in the room and the use of PCM was to absorb cooling load and reduced the room temperature. Some calculations were performed in different cities and it could be found that this technique could reduce energy for cooling between 10 and 87% depended on the air flow rate. Arkar et al. [6] designed a latent heat storage (LHTES) integrating

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Abbreviations and symbols

Nomenclature

A	area, (m^2)
Cp	specific heat capacity, (kJ/kg K)
D	diameter, (m)
e	the correction space value of PCM ball bed (Void faction)
G	mass flow rate per area, (kg/s m^2)
h	enthalpy, (kJ/kg)
h_v	convection heat transfer coefficient, (W/m^3 K)
$\dot{m}$	mass flow rate, (kg/s)
T	temperature, (°C)
W	work, (kW)
x	distance, (m)
Q	heat capacity, (kW)

Greek symbol

ρ	density, (kg/m^3)

Subscript

a	air
AC	air-conditioner
ave	average
amb	ambient
b	bed
Comp	compressor
e	electrical power
E	evaporator
i	input
L	liquid
n	node
o	output
PCM	phase change material
S	solid
Sys	system
th	thermal
r	room

into a mechanical ventilation system. The storage medium was a type of paraffin encapsulated in spheres. The LHTES stored coldness of ambient air during the night and supplied it with time delay during the day thus free cooling was obtained. A case study of a low energy one family building in Slovenia was carried out. The technique maintained the room temperature to be lower than that of the ambient temperature and the free cooling helped reducing the size of mechanical ventilation system. Since PCM could act as thermal energy storage in buildings. The storage medium could store coolness using nighttime cheap electricity and the coolness could be used during daytime for space cooling. Yamaha and Misaki [7] proposed an air distribution system with PCM in air ducts for peak load shaving. The PCM storage was charged from 5:00 am to 8:00 am (the charging mode) by the air flowing in the closed loop of the PCM storage tank and the air conditioner to solidify the storage medium. When the charging operation finished, the ordinary air-conditioning operation started, in which the air was bypassed the PCM storage tank and fed into the occupied room. The discharging operation was occurred from 13:00 pm to 16:00 pm. At this mode, the air after the air-conditioner at a temperature slightly higher than that of the PCM melting point would flow through the PCM tank and the room, respectively. The simulation study based on a part of one floor of an office building in Japan showed that the use of 400 kg PCM for a room with an area of 73.8 m^2 surface could maintain a constant indoor temperature without using any cold source in a hot summer day. The melting temperature suitable for the system was around 19 °C, which could be achieved by MT 19.

In this study, a concept similar to Yamaha and Misaki [7] was considered with the climate of Chiang Mai, Thailand which was hotter than that of Japan and the countries reported in the literatures. The design of the PCM bed was a pack of PCM balls similar to that of Arkar et al. [6]. A set of tubes as a by-pass for air flowing to reduce the pressure drop was respected combining with the PCM bed. An experimental study was performed in a tested room with a cooling load around 2 TR and the electricity cost for the normal system and the system with the PCM had been investigated.

2. Materials and methods

In this study, paraffin waxes melting point at 20 °C (Rubitherm20, RT-20) was selected to be the storage medium to improve the cooling performance of the air-conditioner because the melting temperature point of PCM was lower than the return air temperature and it was higher than the supply air in the charging mode. The property of PCM is given in Table 1 and Fig. 1. Fig. 2 also shows the PCM ball in this experiment which is made from celluloid and contained the paraffin waxes into the PCM ball at around 70% by volume.

Table 1
Descriptions of the paraffin waxes property [8–10].

Paraffin	Properties
Paraffin melting peak point (°C)	22
Freezing peak point (°C)	20
Heat of fusion (kJ/kg)	160–180
Density liquid (kg/l)	0.75
Volume expansion	10%

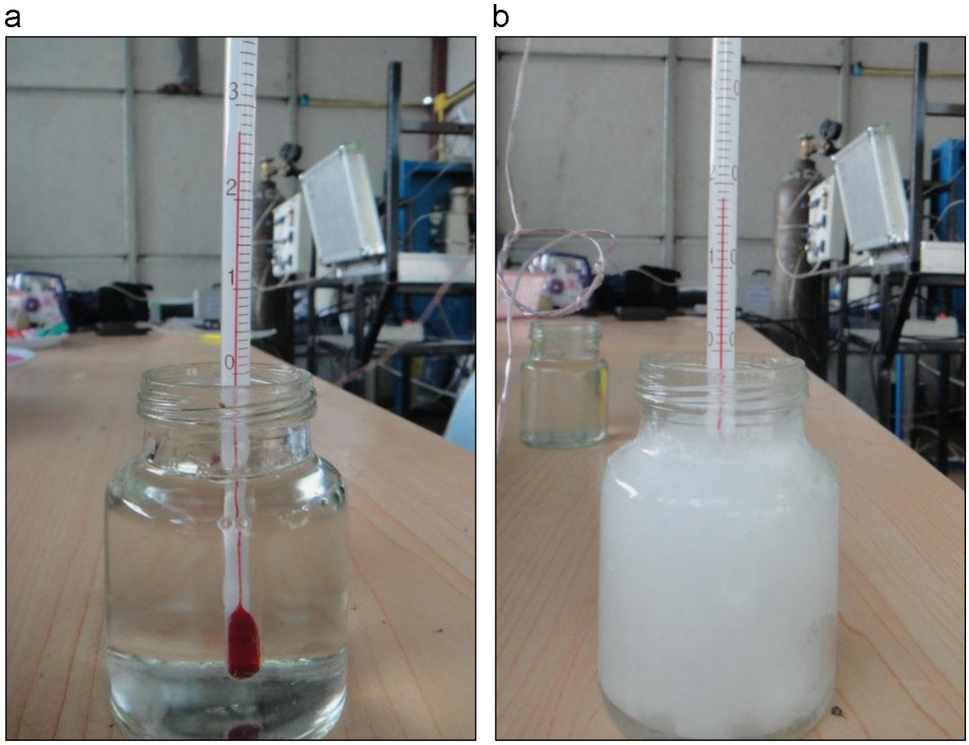

Fig. 1. The liquid and solid phases of paraffin waxes at temperature around 27 °C and 18 °C, respectively [11].

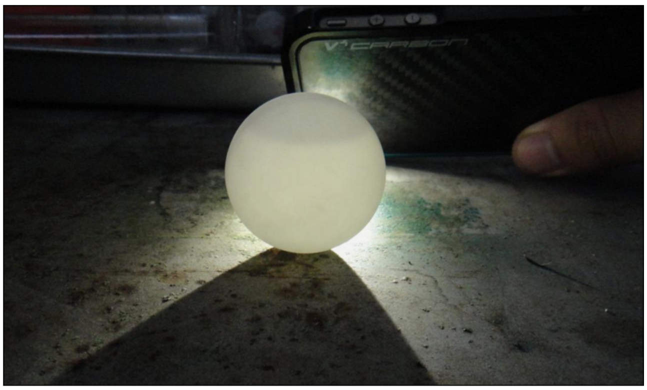

Fig. 2. The PCM ball used in the PCM bed.

An experimental test room with dimensions of 2.4 m × 3.6 m × 2.5 m was constructed. The walls and the ceiling were made from polystyrene foam (Isowall) with a thickness of 7.5 cm and a density of 1 b/ft^3 and both sides were covered with galvanized steel and white polyester coating. A conventional R-134a air-conditioner at cooling capacity 2 TR (24,000 BTU/h) with air-cooled condenser was installed at external of testing room. The load came from an electrical heater with temperature controller. The air-conditioner unit used to cool air entering into the room and froze a storage medium which was a set of paraffin balls contained in a packed bed storage tank. The concept of similar to Yamaha and Misaki [7] as shown in Fig. 3(a) was adapted. The PCM storage was installed below the air-conditioner because the nighttime ambient temperature (around 25–30 °C) in Chiang Mai, Thailand was mostly higher than the PCM melting point (around 19–22 °C). Therefore, in the charging mode, the supply air from the evaporator was used to cool and solidified the PCM storage during the off-peak period as shown in Fig. 3(b). During the daytime, the ambient temperature of Thailand is almost higher than 25 °C as shown in Fig. 4 [12]. Thus, the air-conditioner was used to control the air entering the room at temperature around 15–20 °C. The return air at temperature around 22–25 °C at slightly higher than the PCM melting point (temperature around 20 °C) was fed through the PCM bed as shown in Fig. 3(c). Then, the return air entering the evaporator at temperature around 20 °C would have the lower temperature than the normal system at temperature around 25 °C which meant that the cooling load was reduced. Thus, the electrical power consumption of the air-conditioner could be reduced.

In this study, R-134a air conditioner of 2 TR (24,000 BTU/h) with the air-cooled condenser was tested its performances as the reference unit compared with the new design unit that there was an integrated PCM storage. Table 2 also shows the description of the air-conditioner components.

The storage medium is a paraffin having the melting point of around 19–22 °C which contains in a set of plastic balls kept in a packed bed as shown in Fig. 5. The pressure drop of the air flowing through the bed was considered. If it was too high, there would be a set of by-pass tube along the height of the storage bed. This concept had been used successfully in a PCM bed sensible heat storage [10]. The size of the storage tank would be varied depending on the cooling load and the air flow rate.

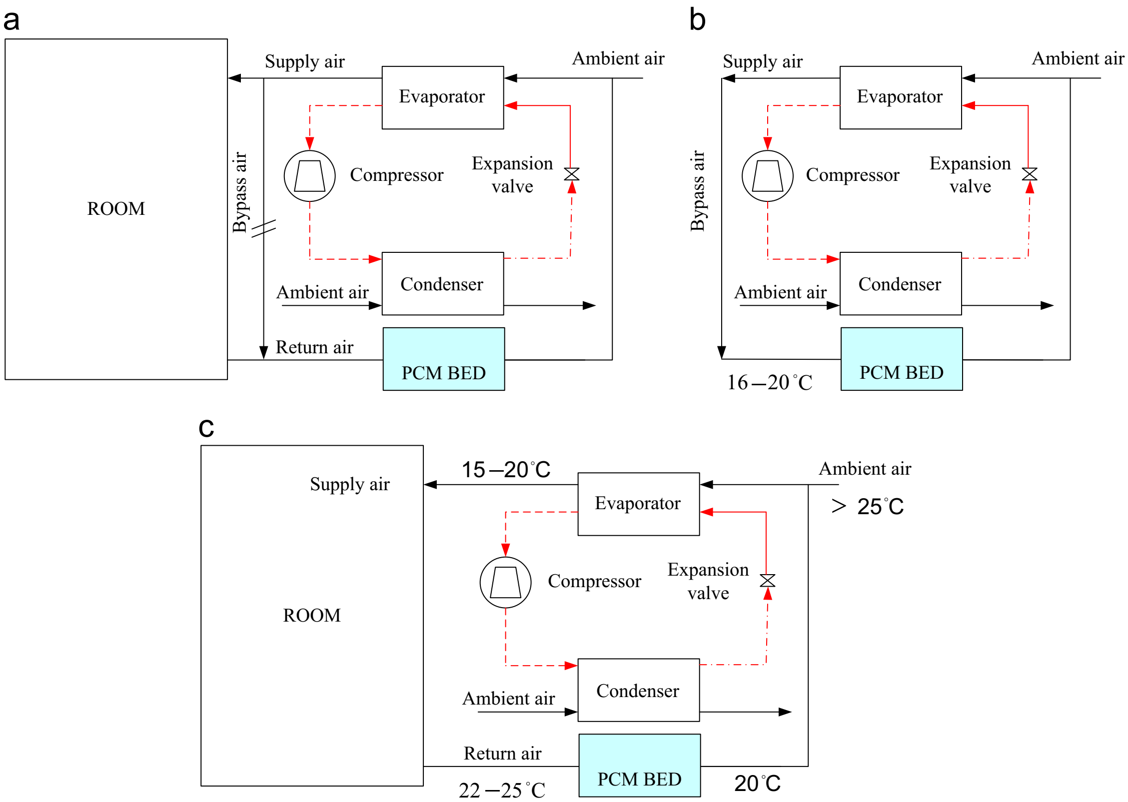

Fig. 3. Schematic of the testing room. (a) The modified system, (b) Charging operation and (c) Discharging operation.

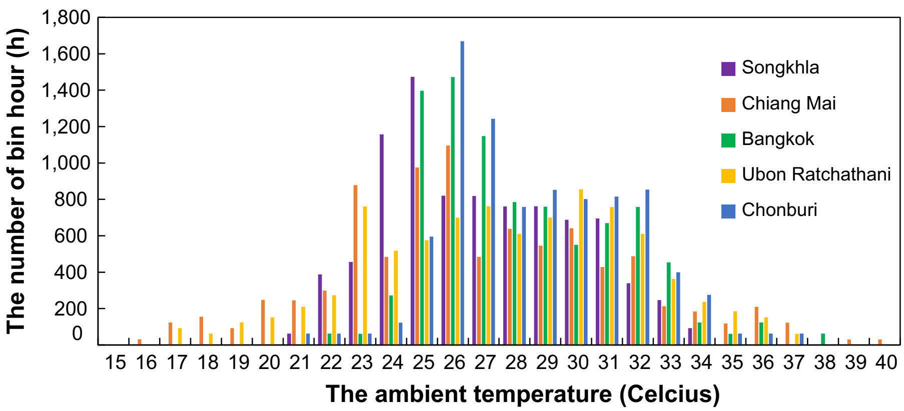

Fig. 4. The bin data of the ambient temperature of the main provinces in Thailand.

From Fig. 5, the thermal storage could be represented by the simply model in Fig. 6. The air entering the thermal storage bed transfers heat to PCM which could be calculated the air temperature leaving the PCM bed by theory of energy balance and heat transfer equation as follows:

$$\dot{m}_a Cp_a dT_a = h_v (Adx)(T_{b,n} - T_a), \tag{1}$$

$$h_v = a\left(\frac{G}{D_b}\right)^b, \tag{2}$$

$$G = \frac{\dot{m}_a}{A}, \tag{3}$$

$$\frac{dT_a}{dx} = \left(\frac{h_v A}{\dot{m}_a Cp_a}\right)(T_{b,n} - T_a). \tag{4}$$

Table 2
Description of air-conditioner components.

Devices	Type	Material	Properties
Fan coil	Fin and tube heat exchanger	Copper and aluminium	Capacity 7.032 kW Tube size (OD) 5.0 mm Fins per inch 18 (FPI) No. of rows and column 2R, 15C
Compressor	Hermetic (rotary) compressor R-134a	Cast iron	Capacity 2.868 kW Compression ratio 6.0 Max
Condenser	Fin and tube heat exchanger	Stainless steel	Capacity 5.275 kW Tube size (OD) 7.0 mm Fins per inch 18 (FPI) No. of rows and column 2R, 36C
Expansion valve	Orifice type thermo static	Bronzed	Capacity 7.032 kW Pressure ratio 3.00

Fig. 5. Installing the PCM bed in the return duct.

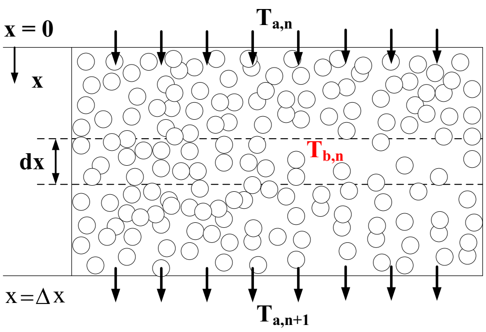

Fig. 6. Energy balance in the thermal storage.

Boundary condition of the PCM is assumed as:

$$BC_1 : x = 0 \rightarrow T_a = T_{a,n}, \tag{5}$$

$$BC_2 : x = \Delta x \rightarrow T_a = T_{a,n+1}, \tag{6}$$

$$\frac{T_{a,n+1} - T_{b,n}}{T_a - T_{b,n}} = \exp\left(-\frac{h_v A}{\dot{m}_a C p_a} \Delta x\right), \tag{7}$$

$$T_{a,n+1} = T_{b,n} + (T_{a,n} - T_{b,n}) \times \exp\left(-\frac{h_v A \Delta x}{\dot{m}_a C p_a}\right). \tag{8}$$

Thus, the convection heat transfer coefficient could be shown by equation as:

$$\dot{m}_a C p_a (T_{a,n} - T_{a,n+1}) \Delta t = \rho_b A \Delta x (1 - e) \Delta h, \tag{9}$$

$$\Delta h = \frac{\dot{m}_a C p_a (T_{a,n} - T_{a,n+1}) \Delta t}{\rho_b A \Delta x (1 - e)}. \tag{10}$$

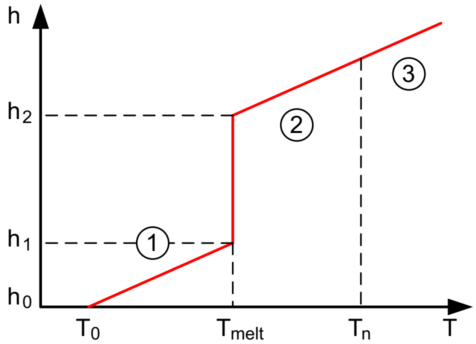

Fig. 7. Enthalpy and temperature profile of PCM.

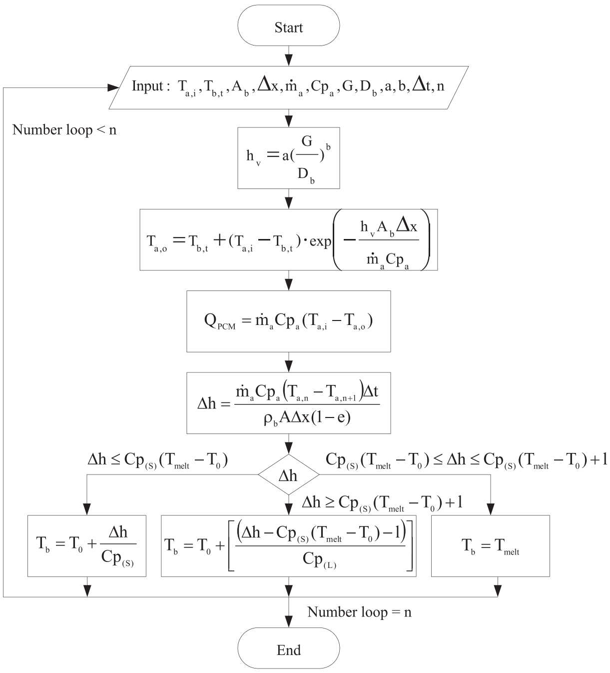

Fig. 8. Flow chart for evaluating the PCM bed temperature and the air leaving PCM bed temperature.

From the performance of PCM, it is found that the temperature of PCM varies with the phase change of PCM as shown in Fig. 7. Thus, the PCM bed temperature of each period could be calculated by enthalpy as follows:

Period 1, the variant temperature of PCM at solid phase:

$$\Delta h \le Cp_{(S)}(T_{melt} - T_0), \tag{11}$$

$$T_b = T_0 + \frac{\Delta h}{Cp_{(S)}}. \tag{12}$$

Period 2, the melting point of PCM:

$$Cp_{(S)}(T_{melt} - T_0) \le \Delta h \le Cp_{(S)}(T_{melt} - T_0) + l, \tag{13}$$

$$T_b = T_{melt}. \tag{14}$$

Period 3, the variant temperature of PCM at liquid phase:

$$\Delta h \ge Cp_{(S)}(T_{melt} - T_0) + l, \tag{15}$$

$$T_b = T_0 + \left[\frac{\left(\Delta h - Cp_{(S)}(T_{melt} - T_0) - l\right)}{Cp_{(L)}}\right]. \tag{16}$$

The step for calculating the thermal storage performance of PCM ball is shown in Fig. 8. For calculation, the properties of the air entering bed and PMC were used to find out the PCM bed temperature and the air leaving PCM bed temperature.

3. Results and discussion

3.1. Pressure drop

Table 3 shows the measuring data of pressure drop between the PCM bed at various thicknesses of PCM bed and the diameter of bypass tube. It could be seen that pressure drops of the bed with and without bypass tubes were almost constant. Therefore, the bed without bypass tubes was chosen in the next study. Moreover, the air velocity of without bypass tubes was rather uniform for the whole cross-section compared with the bed installed bypass tubes.

3.2. Thermal performance of the normal air-conditioner

In this study, the single-stage vapor compression air-conditioner having R-410a as refrigerant had been used to transfer heat of a room temperature and relieve to the environment at a higher temperature level. The specifications of each component of the air-conditioner was shown in Table 2. From the experimental results, it could be found that its energy efficiency ratio (EER_{AC}: a ratio of heat at the evaporator and the electrical power consumption) could be set up as a function of temperature difference between the surrounding ambient (T_{amb}) and the room temperature (T_r) as shown in Fig. 9. The EER_{AC} decreased when the temperature difference of the heat source and heat sink increased. The result was similar to the studies of Kiatsiriroat et al. [13,14]. The EER_{AC} dropped down and an empirical correlation of these parameters could be fitted as:

$$EER_{AC} = -0.2811(T_{amb} - T_r) + 5.7915. \tag{17}$$

Table 3
Pressure drop between the PCM bed for varying the number and the diameter of bypass tube.

Conditions	Pressure drop (in H_2O)		
	Tube 3/8 in.	Tube 6/8 in.	Tube 1 in.
The number of bypass tube at 0 tube			
Δx at 40 cm	0.37	–	–
Δx at 50 cm		0.4	
Δx at 60 cm			0.42
The number of bypass tube at 5 tubes			
Δx at 40 cm	0.36		
Δx at 50 cm		0.35	
Δx at 60 cm			0.36
The number of bypass tube at 10 tubes			
Δx at 40 cm	0.33		
Δx at 50 cm		0.32	
Δx at 60 cm			0.3
The number of bypass tube at 15 tubes			
Δx at 40 cm	0.31		
Δx at 50 cm		0.29	
Δx at 60 cm			0.25

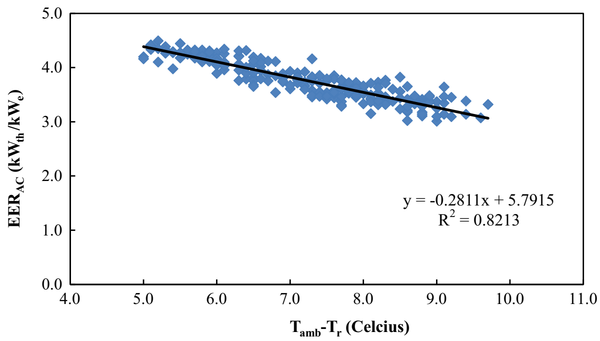

Fig. 9. Thermal performance curve of the normal air-conditioner.

Table 4
Charging and discharging performances of the PCM bed with various thicknesses.

Thickness of the PCM bed	Bed 40 cm	Bed 30 cm	Bed 20 cm
PCM bed			
The number of PCM ball (unit)	1100	933	619
Volume of PCM (l)	57.60	48.85	32.41
Charging time (min)	110	100	70
Discharging time (min)	180	140	80
PCM cooling factor (min/l) *Note: Discharging time/volume of PCM*	3.13	2.87	2.47
PCM charging factor (min/l) *Note: Charging time/volume of PCM*	1.91	2.05	2.16

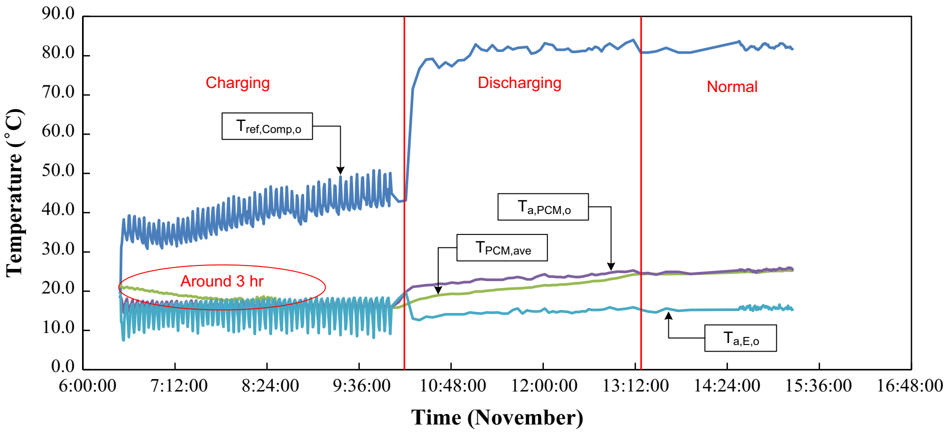

Fig. 10. Temperature profile of the modified air-conditioner at thickness of the PCM bed at 40 cm.

For the consumed electrical power, the value also depended on the temperature of the ambient and that of the air-cooled which was correlated as:

$$W_{Comp} = 0.0829(T_{amb} - T_r) + 2.7851. \tag{18}$$

3.3. Thermal performance of the modified air-conditioner

Table 4 shows the comparison testing results of PCM charging and discharging times with various thicknesses of the PCM bed at 40 cm, 30 cm and 20 cm. The factors for indicating these performances were given in the terms of PCM charging factor and PCM cooling factor, respectively, which were the charging and the discharging periods per unit volume of the PCM. From the table, it could be seen that the charging factor decreased with the increase of the bed thickness and vice versa for the discharging factor.

From the study results, the thickness of PCM bed with 40 cm was chosen because of a high value of the PCM cooling factor. Fig. 10 shows the temperature profile of the air-conditioner units combined with PCM bed at the thickness of 40 cm. It could be seen that the operating cycle of the modified system could be separated into 3 modes which included charging mode, discharging mode and normal mode. In charging mode, the supply air from the evaporator at the temperature around 15 °C was used to cool and solidified the PCM bed during the off-peak period at 6:00–9:00 am around 3 h for the PCM bed thickness of 40 cm. In discharging mode, the return air at temperature around 25 °C was fed through the PCM bed and reduced the air temperature ($T_{a,\mathrm{PCM},o}$) to be around the PCM melting point ($T_{\mathrm{PCM,ave}}$) at about 20 °C. After that the return air at temperature around 20 °C entered the evaporator, it had the lower temperature than the unit without the storage at temperature around 25 °C which meant that the cooling load (Q_E) was reduced as shown in Fig. 11. Thus, the electrical power consumption of the air-conditioner could be saved during the on-peak period after 9:00 am around 3 h for the PCM bed thickness of 40 cm. In normal mode, all the PCM was melted into liquid phase, then the air-conditioning was switched back to the normal air-conditioner to control the air temperature leaving the evaporator.

3.4. Verification of the simulation Results with the experimental data

In the study procedures, the mathematical model of PCM ball bed was developed to predict the thermal performances of the PCM storage. The objective of this procedures was to verify data with the testing data from the constructed of modified air-conditioner.

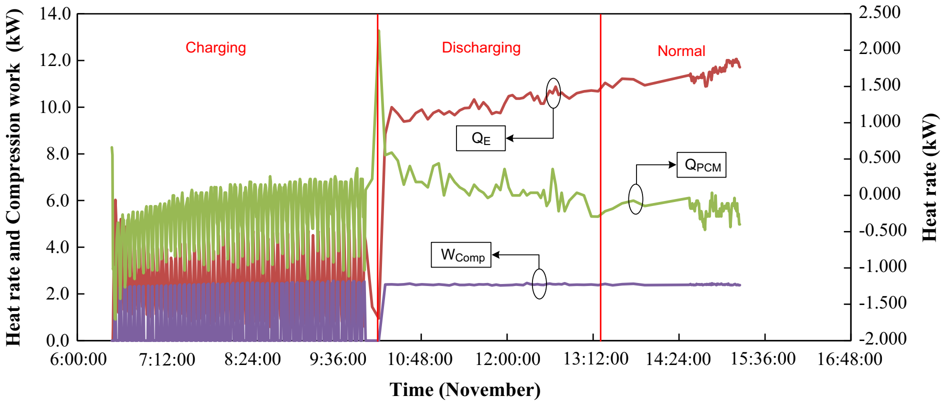

Fig. 11. Cooling capacity of the modified air-conditioner at thickness of the PCM bed at 40 cm.

Table 5
Initial conditions of the mathematical model.

Descriptions	Data	Unit
Bed section area (A)	0.16	m^2
Bed thickness (Δx)	0.4	M
Number loop (n)	3	–
PCM ball diameter (D_b)	0.04	M
PCM density of liquid PCM ($\rho_{(L)}$) [11]	770	kg/m^3
Heat capacity of liquid PCM ($Cp_{(L)}$) [11]	2.3	kJ/kg K
PCM density of solid PCM ($\rho_{(S)}$) [11]	880	kg/m^3
Heat capacity of solid PCM ($Cp_{(S)}$) [11]	2.4	kJ/kg K
Heat fusion ($\Delta h = h_{melt}$) [11]	177.7	kJ/kg
Void fraction (e) [11]	0.4	–
Air velocity flow rate at fan coil ($\dot{m}_a$)	1.415	m/s
Heat capacity of air (Cp_a)	1	kJ/kg K

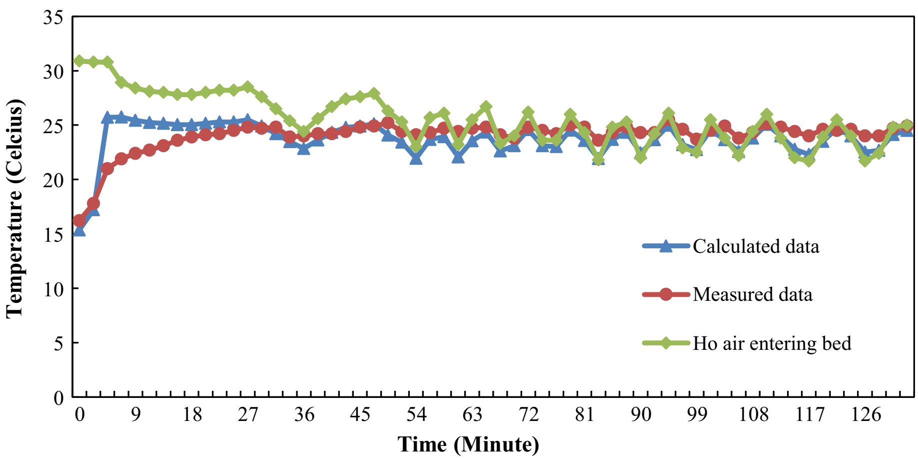

Fig. 12. Comparison results of the measured data and the simulation results of the air leaving PMC bed temperature.

Table 5 shows the initial data of the simulation process to predict behavior of the set of 40 cm PCM unit. Fig. 12 shows the temperature profile of hot air entering the PCM bed ($T_{a,PCM,i}$) which affects to the air leaving PMC bed temperature ($T_{a,PCM,o}$) of the discharging period. Moreover, Fig. 12 also represents the comparison result of the measured data and the simulation result of the air leaving PMC bed temperature. It could be seen that the simulated result agreed quite well with the experimental data at the discrepant around 4.61%. Fig. 13 shows the comparison result of the measured data and the simulation result of the PCM temperature (T_{PCM}) of the discharging period which is effected from the hot air in Fig. 12.

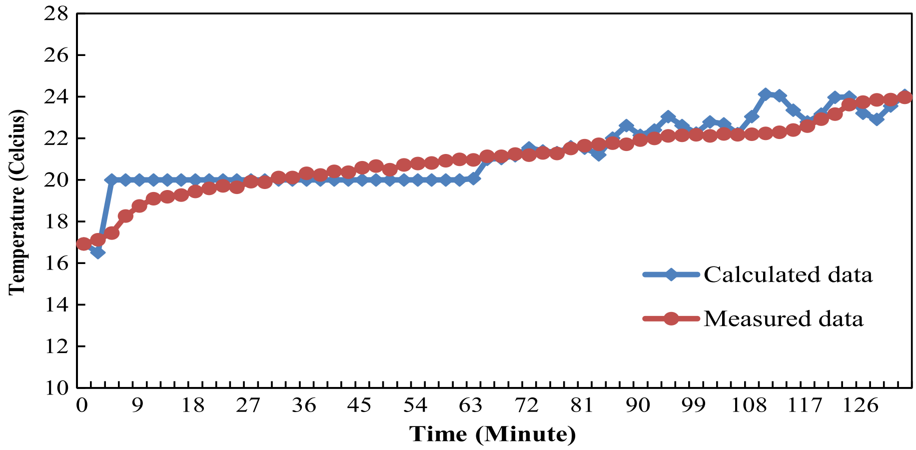

Fig. 13. Comparison results of the measured data and the simulation results of the PCM temperature.

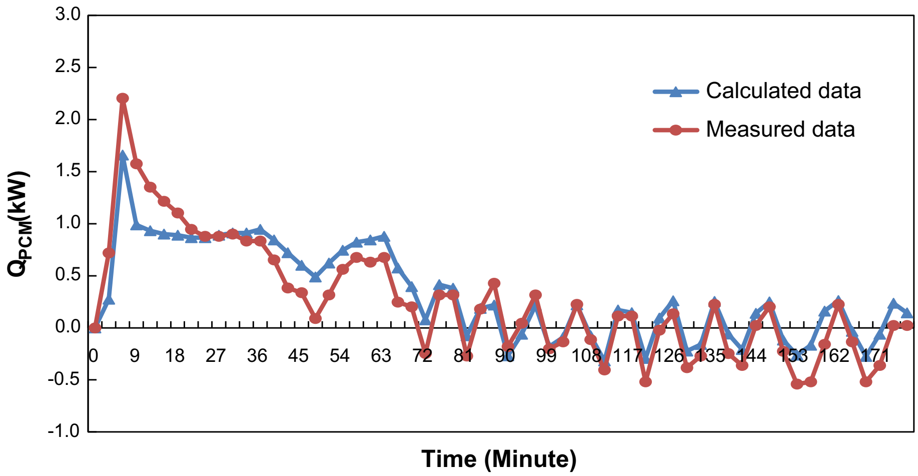

Fig. 14. Comparison results of the measured data and the simulation results of the cooling capacity of PCM bed.

It could be found that the simulated result of the PCM temperature was similarly with the experimental data at the discrepant around 2.73%.

For the cooling capacity of PCM bed (Q_{PCM}), the comparison result of measured data and calculated data was also nearly well as shown in Fig. 14. It could be seen that Q_{PCM} gradually decreased and reached the lower level which meant that the PCM temperature and the air leaving bed temperature gradually increased similarly the results in Figs. 12 and 13, respectively.

From the comparison results, it could be seen that the mathematical model could be used to simulate the performances of the PCM bed that was used to reduce the heat load from evaporator of the air-conditioner. Thus the models would be used to predict the possibilities in using this concept for cooling in a household and evaluated the economic result.

3.5. Economic result

Table 6 also shows the electrical power consumptions of the air-conditioner with and without the PCM bed. It could be found that the average daily electrical power consumption could be saved around 3.09 kW h/d from 39.36 kW h/d of the normal air-conditioner which was around 18.28 baht/d (0.56 USD, 1 USD=32.668 baht) [15] as shown in Table 6.

For the economic analysis of the both models, the general conditions for economic analysis of the systems were as follows:

A. Number of day for using the air-conditioner 300 d/y
B. Electricity charge (Time of use rate: TOU) [16,17] household (1.2.2)

Table 6
Electrical power consumption of the normal system and the modified system.

Air-conditioner	Operating time (h/d)	Electrical power (kW)	Electrical power consumption (kW h/d)	Electricity cost (baht/d)
The normal system	12	3.28	39.36	197.21
The modified system				
Charging period	3	0.84	2.52	5.50
Discharging period	3	1.41	4.23	17.93
Steady period	9	3.28	29.52	155.49
Total	14	–	36.27	178.93
Saving			3.09	18.28

Table 7
The economic results of the modified system.

Descriptions	The normal system	The modified system
PCM cost at 57.6 l (baht)	0	23,040
Electricity cost per year		
Peak 9.00–22.00 o'clock (baht)	40,724.53	36,503.08
Off peak 22.00–9.00 o'clock (baht)	1,534.13	1,838.15
Holiday 0.00–24.00 o'clock (baht)	7,363.81	6,785.70
Ft (baht)	6,966.72	6,271.11
Total cost per day (baht/y)	61,041.17	55,486.65
Saving		
Percentage (%)	–	9.10
Cost (baht/y)	–	5,554.52
Cost (baht/y · TR)	–	2,777.26
Payback period (y)	–	4.15

C. Operating time
The normal air-conditioner system (12 h/d) 8.00–20.00 o'clock
The modified air-conditioner system 15 h/d
Charging mode (3 h/d) 5:00–8:00 o'clock
Discharging mode (3 h/d) 8:00–11:00 o'clock
Steady mode (9 h/d) 11.00–20.00 o'clock

D. Paraffin [18] 400 baht/l.

Table 7 shows the descriptions of the economic results. The electricity saving cost of the modified system was around 9.10% compared with the normal system at 18.28 baht/d (0.56 USD) or 5554.52 baht/y (170.03 USD). While, the PCM cost was around 23,040 baht (705.28 USD) at 57.60 l (400 baht/l or 12.24 USD/l) and the payback period was 4.15 y.

4. Conclusion

From this study, the conclusions are as follows:

1. The PCM ball with using paraffin melting point at around 20 °C could be improved the cooling efficient of the air-conditioner.
2. Pressure drops of the bed with and without bypass tubes was nearly. Thus, the bed without bypass tubes was used for this study.
3. The simulated results of the PCM temperature and the air leaving PCM bed temperature agreed quite well with the experimental data at the discrepant around 2.73% and 4.61%, respectively.
4. The electricity saving cost of the modified system was around 9.10% compared with the normal system at 5554.52 baht/y (170.03 USD), while, the PCM cost was 23,040 baht (705.28 USD) at 57.60 l and payback period was 4.15 y.

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